IMPROVED GAS TURBINE PERFORMANCE

by

CONTROL OF STRAIN RATES

Eighth and Final Report

Imperial College of Science, Technology & Medicine, UK

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SUMMARY

The three main findings of the research of this contract were the identification of combustion oscillations caused by high strain rates and consequent near-periodic extinction and relight, the effect of oscillations on emissions of nitrous oxides, and the quantification of the extent to which the amplitude of the oscillations could be reduced by practically acceptable methods. In addition, consideration has been given to the development of calculation methods to represent the oscillating flows and to guide the development of control procedures. The overall outcome is the ability to control, with comparatively simple procedures, combustion oscillations with premixed methane and air burning in a duct with a sudden expansion and stemming from a combination of acoustic and stabilization effects.

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PREAMBLE

The proposed tasks have been addressed with emphasis on those that provided explanations for physical phenomena and thereby allowed the development of an approach to control. Thus, extensive experiments were performed first to examine the nature of the dynamic effects that are known to occur with the combustion of lean mixtures, as described in the references to the research of this Contract by De Zilwa *et al.* (2000, 2001), and much of the second year was devoted to the consideration of methods that would lower the amplitudes of the oscillations, Emiris (2002) and Emiris *et al.* (2002).

The research began with a background of experience that had revealed difficulties in controlling acoustic oscillations with equivalence ratios close to unity, De Zilwa, Sivasegaram and Whitelaw (2000). In particular, closed-loop control had proved to be successful in ameliorating acoustic oscillations with modest heat release but less so as the heat release was increased and apparently due to modulation of the near-single frequency signal. At the same time, it was known from the experiments in a sector of a gas turbine, Poppe et al (1998), that out-of-phase pulsation of the fuel supply to neighbouring fuelling devices could reduce oscillation amplitudes considerably so that comparatively simple methods could be effective if the flow phenomena were understood. A basis for understanding had been provided in previous Army contracts in which the effects of strain rate on extinction had been examined with opposed flames, Sardi and Whitelaw (1999) and Sardi *et al.* (2000), and this research also justified the continuing study of premixed flames with their comparative geometric simplicity and known relationship to non-premixed flames. The foundations of the experimental methods had also been laid over many years and their extension to the study of sudden-expansion flows with and without combustion, Khezzar *et al.* (1999), ensured that a range of techniques was available and with experience of difficulties and ways to overcome them.

The reason for burning lean mixtures is usually to reduce the emissions of nitrous oxides generated at high temperatures and dependent upon the residence time at these temperatures. It was known from the research of Poppe *et al.* that lower NOx concentrations were obtained with higher amplitudes of oscillation and preliminary explanations were provided. This research was extended here to support the earlier findings and to extend them to near-extinction situations where it was found that the effect was reversed and the unwanted dynamic effects increased NOx concentrations as well as the possibility of physical damage.

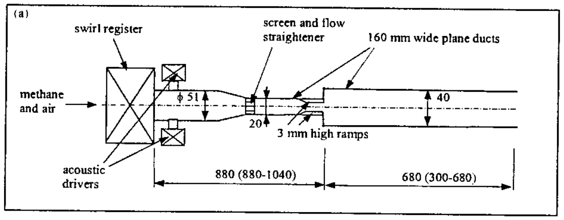
The final topic was consideration of calculation methods to represent the oscillations and this began with the unsteady laminar and turbulent flows downstream of symmetric sudden expansions in plane ducts. It began with the formulation of a computer method to solve the unsteady equations appropriate to isothermal sudden expansion flows and ended with the conclusion that a much longer program of research was required to make the necessary impact on combusting flows. A new contract is in place to allow this development and to guide the control efforts that involved *ad hoc* selection and testing of some methodology.

THE NATURE OF COMBUSTION OSCILLATIONS

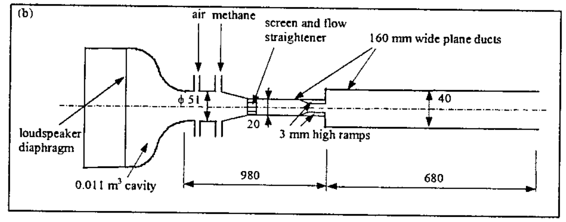
The following is a much shortened version of the paper by De Zilwa *et al.* (2001) and intended to provide an indication of the research and its findings.

Flow configurations and instrumentation

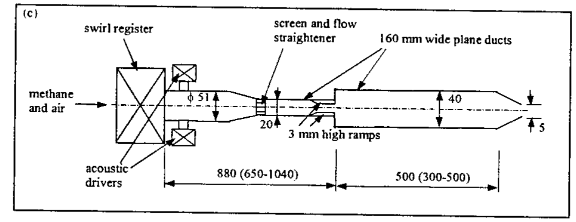
The experiments were conducted in the ducted arrangements of figure 1 with flames stabilised by plane and round sudden-expansions and by a disk. The upstream and downstream duct lengths are indicated on the figure, with a range where appropriate.



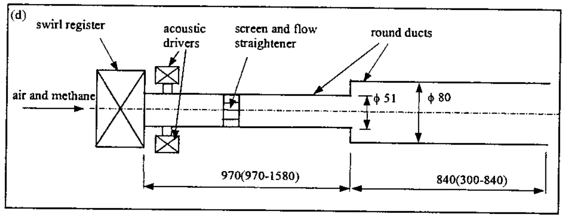
Plane sudden-expansion configuration with acoustically-closed upstream end and facility for oscillating pressure field.



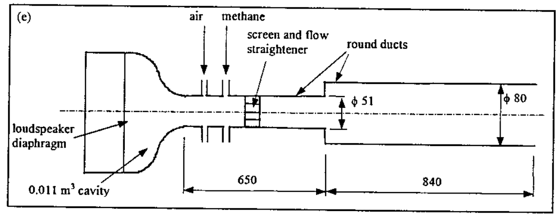
Plane sudden-expansion configuration with acoustically-open upstream end and facility for oscillating pressure field.



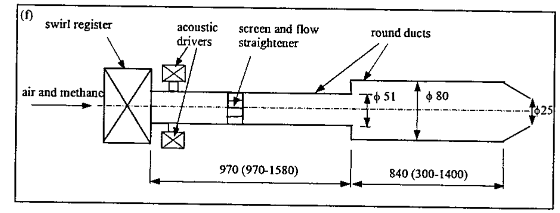
Plane sudden-expansion configuration with acoustically-closed upstream end, constricted exit and facility for oscillating pressure field.



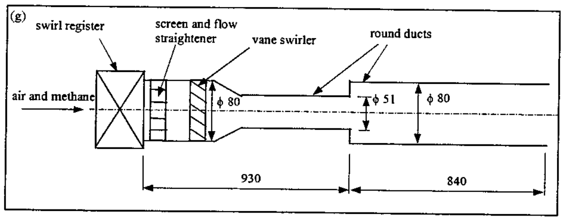
Round sudden-expansion configuration with acoustically-closed upstream end and facility for oscillating pressure field.



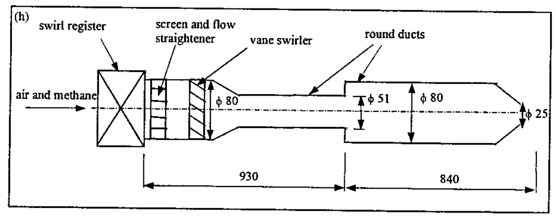
Round sudden-expansion configuration with acoustically-open upstream end and facility for oscillating pressure field.



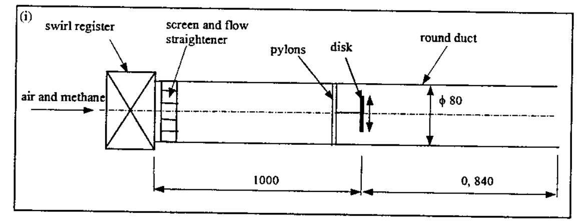
Round sudden-expansion configuration with acoustically-closed upstream end, constricted exit and facility for oscillating pressure field.



Round sudden-expansion configuration with acoustically-closed upstream end and facility for introducing swirl.



Round sudden-expansion configuration with acoustically-closed upstream end, constricted exit and facility for introducing swirl.



Configuration with disk-stabiliser.
The 25 mm nozzle could be used to constrict the duct.

Figure 1: Flow configurations.
*Not to scale. All dimensions in mm except where indicated otherwise.

The plane sudden expansion comprised duct heights immediately upstream and downstream of the expansion of 14 and 40 mm, respectively. The upstream end could be acoustically closed with a swirl register as in figure 1a, or acoustically open with an area expansion of over 30 from the upstream duct to a 0.011 m^3 cavity, figure 1b. The downstream end of the ducts could be open, as in figure 1a, or constricted with a 5 mm nozzle, figure 1c. A 40 mm high by 100 mm long quartz window was fitted immediately downstream of the expansion to provide optical access to the flame.

The corresponding round configurations of figures 1d-f had upstream and downstream duct diameters of 51 and 80 mm and an exit nozzle diameter of 25 mm. A 20 mm high by 125 mm long quartz window could be introduced immediately downstream of the expansion to provide restricted optical access to the flame. The configuration of figure 1i comprised a 56 mm disk mounted within an 80 mm diameter duct, with the upstream end acoustically-closed, and again the duct exit could be constricted with the 25 mm nozzle. As with the round sudden-expansion configurations, optical access was limited when the downstream duct was used and a few experiments were conducted without this duct so as to provide unhindered access.

Air and methane were supplied by compressors and their flow rates were regulated to a precision of 3 % by calibrated rotameters (Rotameter Manufacturing Co. and KDG). Honeycomb flow straighteners and screens were placed close to the upstream ends of the combustors to remove swirl. The mass flow rate through the combustors is presented in terms of Reynolds number based on the velocity and on the diameter and equivalent diameter of the duct just upstream of the flame holder for the round and plane configurations, respectively. Swirl was introduced into the round sudden-expansion flows of figures 1g and h by mounting a vane swirler downstream of the flow straightener and within the 80 mm diameter pipe at the upstream end of the combustor.

Oscillations were imposed at a pre-determined frequency on the pressure field of the sudden-expansion flows by the pair of acoustic drivers shown in figure 1a and the loudspeaker of figure 1b, both driven by amplified signals from a function generator (Philips PMS132). Active control was also attempted by the imposition of out-of-phase oscillations, with feedback from a pressure transducer and two controllers, one based on an analogue phase-lock loop and a second involving real-time digitisation (National Instruments PC-1200) and processing (Pentium, 450 MHz).

The pressure fluctuations were measured by a water-cooled piezo-electric pressure transducer (Kistler 6121 with charge amplifier 5007) mounted on the wall of the duct 50 mm upstream of the flame holder. The pressure signals were digitised by a 12-bit A/D converter (National Instruments PC-1200) with a sampling rate of 1024 Hz or 4096 Hz when frequencies exceeded 100 Hz. Flame movements were examined in terms of the signal from a photomultiplier that measured local light emission with a spatial resolution of 2 mm. The signal was amplified (Brandenburg 2475R) and digitised simultaneously with that from the pressure transducer.

The structure of the flames was determined in terms of the relative distribution of reaction by visualising the chemiluminescence of the CH radical emitted at 429 nm with an optically-filtered CCD camera. With the continuous oscillations close to stoichiometry the imaging was triggered on the pressure signal and averaged over 100 images at the same phase position in the cycle. The flames close to the limits were characterised by a series of images. The CCD camera was triggered by a continuous pulse train from a generator (Thandor TG 105) and records of the pulses and of the pressure transducer signal were acquired simultaneously, so that the images could be related to the position in the pressure cycles at which they were obtained.

Concentrations of NOx in the exit plane of the round sudden-expansion arrangements were measured with a water-cooled stainless-steel suction probe and a chemiluminescence detector (Thermo-Environmental Instruments 42), and the uncertainty in the time-averaged results was less than 2 ppm.

Results

The **extinction limits** and other characteristic features of the flames in the plane and round ducts with acoustically-closed upstream boundaries and without and with an exit nozzle were observed and details measured in terms of pressure and chemiluminescence. The branches of flame behind the two steps of the unconstricted plane configuration of figure 1a extinguished at different equivalence ratios as the lean-flammability limit was approached with equal probability that one would extinguish before the other. The flammability range narrowed with increasing flow rate due to the increasing bulk strain. Both branches gave rise to a flapping motion immediately prior to its extinction, with both moving in the same direction at the same instant. This was associated with longitudinal oscillations and consequent strengthening and weakening of the branches of flame, out-of-phase with each other and, similarly when the flammability limit was reached, the remaining branch of flame again oscillated longitudinally and also laterally across the width of the duct before blowing off. These observations emphasise the three-dimensional nature of the near-limit oscillations. The frequencies of these flame movements were of the order of 10 Hz and increased with flow rate. Changing the upstream boundary to be acoustically open, as in the duct of figure 1b, did not change the phenomena associated with flame extinction. The range of flammability in the constricted was around 30 % less than that in the unconstricted duct, figure 2b, and the two branches of flame oscillated axially with the same phase and then extinguished together as the equivalence ratio was lowered towards the lean-flammability limit. The equivalence ratio at extinction was around 0.68, higher than the 0.65 associated with the extinction of the first branch of flame in the unconstricted duct, and this implies greater heat release with a more symmetric flow. The flame movements preceding extinction in the constricted duct

included strong flashback of the flame upstream of the expansion and were accompanied by a series of large-amplitude explosions.

The extinction limits with the unconstricted round duct and an acoustically-closed upstream end were different from those of the plane duct in that the entire flame blew off the expansion at one time, consistent with the single toroidal recirculation zone behind the expansion. The equivalence ratios of the limits are similar to those of the plane duct, and longitudinal and azimuthal oscillations of the flame preceded extinction with frequencies similar to those in the plane duct. As with the plane ducts, constricting the duct exit narrowed the flammability range and gave rise to a series of large-amplitude explosions prior to extinction and, when the upstream end was acoustically open, the nozzle could not be introduced without the flame blowing off.

A region of equivalence ratio around unity and above a threshold flow rate gave rise to continuous large-amplitude oscillations in all cases and the boundaries of their occurrence were marked by a sharp increase in the amplitude. The frequency of these large-amplitude oscillations was of the order of 100 Hz and changed with upstream and downstream duct length and boundary conditions that corresponded to characteristic acoustic lengths and impedances.

With Reynolds numbers less than 51,000 and also close to the rich limit of large-amplitude combustion, the dominant frequencies were around 115 and 340 Hz and corresponded to the quarter-wave three-quarter wave frequencies of the duct. The association of the large-amplitude oscillations with these acoustic modes was confirmed by measuring their waveforms along the length of the duct, by the increase of the dominant frequencies with decrease in the upstream and downstream duct lengths, and by their independence from flow rate. It should be noted that the maximum amplitude of the acoustic waves could be limited by selection of the upstream and downstream duct lengths and a maximum rms amplitude of 2 kPa was chosen to allow operation with windows over long times.

Low-frequency modulations of the pressure signals were evident and increased with flow rate. The period of these modulations varied by more than 50 % when the upstream end was acoustically closed, and by much less when it was acoustically open and they occurred at the bulk-mode frequency of the upstream cavity of around 30 Hz. These low-frequency modulations were associated with low-frequency movements of the flame front as shown by the fluctuations of photomultiplier signals and were consistent with high amplitudes of oscillation and, hence, high strain rates and local extinction close to the step. The downstream translation of the flame led to smaller amplitudes of oscillation since the region of heat release moved away from the antinode, and the flame was then able to move back towards the step. Thus, the largest pressure fluctuations occurred when the flame was closest to the step, consistent with the coincidence of the largest pressure amplitudes and strongest light emission. This suggested that the decrease in amplitude was associated with the flame movement away from the step and the increase with the movement towards it. Thus, the times associated with these changes in amplitude from the pressure signals were around 0.009 s and 0.022 s and provided estimates for those of the flame movements. As mentioned previously, excursions of the flame up to 20 mm from the step were observed and the time required for the flame to move this distance at the 5 m/s average flow velocity of the shear layer was 0.004 s. Similarly, the time for it to travel back to the step at the burning velocity of the mixture was around 0.5 m/s and similar estimates were obtained from the pressure signals.

Pressure measurements in the round ducts of figures 1d and e showed that the nature of the acoustic oscillations close to stoichiometry and the low-frequency modulations, were similar to those in the plane ducts. The large-amplitude oscillations with the acoustically closed upstream-end configuration of figure 1d were associated with the three-quarter wave in the entire duct, though the quarter-wave became increasingly dominant with shorter duct lengths.

The discussion of extinction limits identified flow conditions outside the envelope of large-amplitude combustion that also gave rise to discrete-frequency oscillations, but with peak-to-peak amplitudes less than 1 kPa. The cycle-resolved flame structure showed vortex rollup and growth but, in contrast to that in the presence of the acoustic oscillations, the vortices were convected downstream without stretching. Typical pressure signals showed that the modulations were much smaller than with acoustic oscillations, due to the lower energy-release rates and these oscillations were also different in that the dominant frequency was independent of changes to the upstream and downstream duct lengths, and hence, were not associated with acoustic modes. The dominant frequency decreased as the equivalence ratio was changed from stoichiometric mixture fractions toward the lean and rich flammability limits so that, for example at a Reynolds number of 39,000, it decreased from 100 Hz at an equivalence ratio of unity to 85 Hz at 0.8. It also increased with flow rate and the dependence of frequency on flow condition suggests that the oscillations were associated with fluid-dynamic instabilities though their proximity to the fundamental frequency of the duct, the 100 Hz quarter-wave, suggests that they were amplified by duct resonance. Similarly, when the upstream end was acoustically open, the corresponding oscillations had frequencies close to the 155 Hz of the dominant half-wave.

As the equivalence ratio approached that of **the lean-flammability limit**, the branches of flame behind the two steps of the plane expansion extinguished non-simultaneously and gave rise to oscillations prior to the extinction of each. The oscillations preceding the extinction of the second branch of flame were characterised by the CH chemiluminescence images, which showed longitudinal movements between 0.9 and 3.2 step heights (12 to 42 mm) at the Reynolds number of 57,000, that these longitudinal movements gave rise to a strengthening and weakening of the entire flame, and that the flame was strongest when it was stabilised closest to the step. These flame movements caused a pressure maximum corresponding to the flame position closest to the step and to the strongest flame and, as with the flame movements that

modulated the acoustic oscillations close to stoichiometry, the time scales associated with the fall and rise of pressure (0.010 and 0.19 s) provided estimates for the times of the flame movements away from and back towards the step. It was again clear that the burning velocity was much less than the velocity of the flow and, hence, the flame movement towards the step controlled the period of the oscillation.

The oscillations of the flames preceding **extinction in the round duct** of figure 1d, also gave rise to low-frequency pressure fluctuations and rise-and-fall similar to those in the plane duct. The average frequency increased with flow rate from around 5 Hz at a Reynolds number of 34,000, based on velocity and duct diameter upstream of the expansion, to 8.8 Hz at 67,000 and the higher frequencies in the round duct were consistent with the shorter mean reattachment lengths of around 3.5 step heights, which corresponded to reattachment at 52 mm compared with 61 mm in the plane duct

The growth in amplitude as extinction was approached, for example from around 0.2 kPa five cycles from extinction to around 0.4 kPa in the cycle immediately prior to extinction at the Reynolds number of 49,000, was clearer than in the plane duct. The amplitudes also increased with flow rate so that the amplitude of the final oscillation at the Reynolds number of 67,000 was around 0.8 kPa. The growth in amplitude was associated with increased travel by the flame as extinction was approached, consistent with the increasing period of oscillation, and with weakening with every cycle of oscillation. This was consistent with the results of Sardi and Whitelaw (1999) who showed weakening of their opposed jet flame with every imposed cycle and thus, the flame had to travel further from the step before it could re-establish itself. The amplitudes in the round duct were higher due to the stronger recirculation zone and the consequently higher concentration of heat release close to the step and to the pressure antinode.

The frequency of the large-amplitude oscillations that occurred with near-stoichiometric mixtures at high flow rates in the constricted plane duct of figure 1c was around 95 Hz, and pressure measurements along the length of the duct showed that these oscillations corresponded to a quarter-wave in the upstream duct and that constant pressure amplitudes along the downstream section were consistent with bulk-mode behaviour. The quarter-wave dominated but, with the larger contraction ratio of the round duct, 10 rather than 8 in the plane duct, the bulk-mode oscillation of the cavity between the nozzle and the expansion plane dominated at around 50 Hz.

Low-frequency flame movements immediately prior to lean extinction in the **constricted plane duct** gave rise to pressure fluctuations with average frequencies that increased from around 4.3 to 5 Hz as the Reynolds number was increased from 31,000 to 39,000. They were similar to those in the unconstricted duct and the higher frequencies, for example 5 instead of 4.4 Hz at the Reynolds number of 39,000, were due to the 25 % faster burning velocity at the higher equivalence ratio of extinction. They were modulated by a frequency of around 70 Hz, which increased with decreasing downstream duct length and was determined to be the bulk-mode frequency of the combustor cavity. The importance of this frequency close to the limit is in contrast to the situation close to stoichiometry where the upstream quarter-wave dominated. The amplitude of these bulk-mode oscillations were largest immediately after the pressure minima of the low-frequency cycle, that is when the flame was at its furthest point from the expansion and, hence, when it was least stable, which again is consistent with bulk-modes being most important with weak flame stabilisation.

The amplitude of the low-frequency oscillations increased as extinction was approached and also with heat-release rate, with peak-to-peak fluctuations of up to around 4 and 8 kPa at Reynolds numbers of 31,000 and 39,000, respectively. These amplitudes were two orders of magnitude larger than in the unconstricted duct and were caused by the interaction between the oscillations due to extinction and relight and the bulk mode. This was supported by pressure signals that showed that a downstream duct length of 550 mm gave rise to bulk-mode oscillations with peak-to-peak amplitudes of up to around 2 kPa at a Reynolds number of 39,000, while the same flow rate with a duct length of 350 mm gave rise to bulk-mode amplitudes of 5 kPa and to consistently larger low-frequency oscillations. Chemieluminescent images were obtained over cycles of the bulk-mode oscillation and showed vortex roll-up, growth and collapse. They also show the effect of the low-frequency strengthening and weakening of the flame on which the bulk-mode oscillation was superimposed, with the images of the first cycle much stronger than those of the second. The stronger images occurred immediately prior to the pressure maxima of the low-frequency cycle and the weaker images just after the minima.

Pressure signals in the **constricted round duct** with the downstream 25 mm diameter nozzle exhibited with the average frequency of the oscillations leading to extinction increasing with flow rate from around 5.5 Hz at a Reynolds number of 34,000 to 7.1 Hz at 49,000. These frequencies were slightly higher than those in the unconstricted duct with which the average frequency at the latter flow rate was 6.2 Hz.

The amplitudes of the low-frequency oscillations were much higher than in the unconstricted duct, with peak-to-peak variations of up to 45 kPa compared with 0.4 kPa at the Reynolds number of 49,000. Also, the number of cycles to extinction decreased with increasing flow rate and consistent with Sardi *et al.* (2000) who showed that the number of imposed oscillation cycles required to extinguish their counterflow flames decreased with the imposed amplitude and, hence, with imposed strain. Modulations of the low-frequency oscillations by bulk-mode oscillations of around 40 Hz were also clear and their amplitudes are largest, up to around 10 kPa at the Reynolds number of 49,000, immediately after the pressure minima.

The nature of flames close to extinction was also examined for **disk-stabilised configurations** and the sudden-expansion in the round duct in the presence of **swirl,** since both give rise to different distributions of strain rate and regions of recirculating flows. Similarly, a limited number of flows were examined with propane fuel and its different

flame speed. All provided evidence of low-frequency oscillations with time scales that confirmed periodic extinction and relight and consistent with high strain rates close to the plane of the flame stabilizer. And prior evidence exists with disk-stabilised flames of the modulation of acoustic waves with equivalence ratios close to stoichiometric.

OSCILLATIONS AND NITROUS OXIDES

Concentrations of NOx were measured in the exit plane of the round sudden-expansion without and with the nozzle in place, and decreased as the equivalence ratio was reduced towards the lean limit and with increase in flow rate. Those at equivalence ratios close to that of the lean-flammability limit in the constricted duct, with large-amplitude low-frequency oscillations, were around 50 % larger, than of the more stable flow in the unconstriced duct at the same flow condition. Thus, the average concentration of 8 ppm with pressure fluctuations of less than 0.1 kPa in the unconstricted duct may be compared with 13 ppm in the constricted duct with amplitudes of over 1 kPa, and both at a Reynolds number of 49,000 and an equivalence ratio of 0.69. This suggests that the increased temperature fluctuations due to the oscillations were skewed towards higher temperatures as a consequence of the extinction limit and consistent with the opposite effect with increased fluctuations in the vicinity of the adiabatic flame temperature, Poppe *et al.* (1998).

Corresponding measurements with near-stoichiometric mixtures and high-amplitude oscillations caused substantial reductions in the NOx concentrations measured, with the amplitude of the oscillations reduced by active control, and in accord with the findings of Poppe *et al.*

Thus, oscillations led to smaller concentrations of NOx close to stoichiometry because the maximum temperature was constrained by the adiabatic flame temperature and, even with these reductions, and as expected, the concentrations were higher than with the low flame temperatures close to the lean limit. They could also lead to larger NOx concentrations with lean mixtures due to temperature fluctuations constrained by extinction so that the operating condition for low NOx depends on oscillatory amplitude as well as on mean flame temperature, and the smallest values may be achieved at equivalence ratios above that of extinction, so as to avoid high-amplitude oscillations. This was the case in the constricted duct in which the concentrations of NOx were lowest at equivalence ratios around 0.03 above the limit.

CONTROL OF OSCILLATIONS

The flows examined in the ducts of figure 1 were also used as a basis for examination of control strategies which included the imposition of pressure oscillations, active closed-loop control of imposed pressure oscillations, the addition of small quantities of mixture of fuel and air close to the base of the flame without and with oscillations, and active control and the combination of the best combination of the last with imposed oscillations. The findings are described in abbreviated form in the following paragraphs.

Pressure oscillations with frequencies up to 500 Hz were imposed in the plane and round sudden-expansion flows of figure 1a and d with the pair of acoustic drivers, and of figure 1b and e with the loudspeaker. The best response occurred at the resonance frequencies associated with the acoustic half-waves in ducts with the acoustically-open upstream ends and with the three-quarter-waves in ducts with acoustically-closed upstream ends. In general, imposed oscillations reduced the flammability range. For example oscillations imposed with the maximum allowable input to the loudspeaker at the 120 Hz half-wave frequency of the plane duct of figure 1b, increased the lean limit from 0.53 to 0.59 at a Reynolds number of 39,000 and from 0.59 to 0.61 at 81,000. The smaller effect at the higher flow rate was due to the larger amplitudes of the naturally-occurring oscillation, as quantified in the previous sections, as were the smaller effects of imposing oscillations in the round ducts.

The effect of the imposed oscillations on the time-averaged CH emission from the flame in the plane duct was determined with equivalence ratios close to that of the **lean-flammability limit**. Oscillations with frequencies less than 30 Hz had little effect while forcing at higher frequencies caused the flame to move closer to the step, consistent with a shorter region of recirculation. Forcing also caused the time-averaged region of reaction to widen, as the large vortices shed at the step translated along the shear layer over the period of the imposed oscillation, as demonstrated by cycle-resolved ensemble-averaged images. Pressure signals were measured close to the lean-extinction limit with oscillations imposed at the resonant three-quarter-wave frequencies of the plane and round ducts with the acoustically-closed upstream ends. When the imposed frequency was filtered out, low-frequency oscillations similar to those in the unforced flow were apparent and this suggests that the imposed pressure oscillations did not greatly influence the near-limit oscillations. The frequency of the oscillations was higher with forcing, for example around 10 Hz compared to 5.6 Hz without, at a Reynolds number of 57,000 in the plane duct, and consistent with the shorter recirculation zone. Low-frequency modulations of the imposed oscillations were apparent, and their largest and smallest amplitudes occurred close to the maxima and minima of the low-frequency oscillations, respectively. This implies stronger response to forcing when the flame was close to the pressure antinode at the expansion plane and weaker response when it was further away.

Pressure oscillations were also imposed with the acoustic drivers in **the constricted plane and round ducts** of figures 1c and 1f. With frequencies close to that of the 220 Hz three-quarter-wave in the upstream duct, they reduced the amplitude of the bulk-mode oscillations with **near-stoichiometric mixture** fractions in the constricted round duct,

probably due to the greater stability due to the break-up of the large-scale structures that could be achieved by forcing at relatively high acoustic frequencies. The amplitudes of the bulk-mode oscillations were reduced from around 7 to 1 kPa at Reynolds numbers of 34,000, and from 8 to 5 kPa at 49,000. The same frequencies were imposed close to the extinction limits in an attempt to suppress the large-amplitudes that occurred there, since the transient near-limit oscillations were amplified by this bulk-mode oscillation. They reduced the amplitudes of the bulk-mode oscillation from around 4 kPa to less than 1 kPa at a Reynolds number of 34,000 and those of the low-frequency fluctuations from around 6 to 2 kPa. This resulted in a lower lean-extinction limit of 0.66, rather than 0.69. The effect of the imposed oscillations was less at higher flow rates and, though the amplitudes of the low-frequency oscillations were reduced from 8 to 6 kPa at a Reynolds number of 49,000, the change in the limit was negligible.

Active control with an analogue phase-lock loop controller was again successful with the large-amplitude acoustic oscillations with small modulations and less so as the modulations increased. It was not successful with the highly modulated low-frequency oscillations close to the limits due to the range of frequencies involved. The new control system with digitisation of the pressure signal and processing in real time successfully tracked the flame oscillations close to the limits but was hindered by the inability of the loudspeaker and the acoustic drivers to generate sufficient power at the low frequencies of interest.

The ability to **control** the low-frequency oscillations **with fuel added** close to the plane of the sudden expansion in the round ducts with and without a nozzle was investigated with location of injection, added fuel, addition of fuel-air mixtures and the periodicity of injection as variables.

Injection normal to the duct walls with four 4mm-diameter injectors evenly spaced around the circumference at a location 70mm or 1.4 upstream-duct-diameters upstream of the expansion plane was selected as the preferred of three configurations, based on comparison of pressure spectra and mean temperatures and hydrocarbon concentrations at the duct exit. Injection downstream of the step excited acoustic modes of the duct and combustion was not completed within the length of the combustor. Axial injection in the direction of the mean flow and at the expansion plane increased the imposed strain experienced by the flame was unable to reduce the amplitude of the low-frequency oscillations.

In the open duct with a bulk-flow Reynolds number of 68,000 and an equivalence ratio of 0.65, the amplitude of signals at frequencies up to 90Hz were attenuated by around 1.18 decades. The corresponding reduction in the r.m.s of pressure was about 36%, from 0.47 kPa without injection to 0.30 kPa with 3% of total fuel injected locally. At equivalence ratios closer to stoichiometry and a Reynolds number of 60,000, peak-to-peak pressures were reduced from around 10 kPa without to 7.5 kPa with injection due to the reduction of the amplitude of low-frequency modulations of the acoustic frequency. In the duct constricted by a nozzle and Reynolds number equal to 35,000, injection of less than 4% of fuel increased the lower equivalence ratio at which large-amplitude oscillations occurred by improving flame stabilisation and the r.m.s. was reduced from 1.5 to 0.3 kPa at an equivalence ratio of 0.74 and from 2.4 to 0.75 kPa at 0.9. At equivalence ratios greater than 0.95 There was no reduction in the r.m.s at equivalence ratios greater than 0.95, probably due to the dominance of the bulk-mode oscillation which was at least 3 orders of magnitude greater than any other spectral peaks. These results are important in that they show that carefully located and small quantities of fuel may be injected close to base of unstable flames with improvements in stability over a wide range of equivalence ratios. Thus, it is probable that combinations of low-frequency injection and oscillations imposed at dominant acoustic frequencies will result in worthwhile overall reductions in flame movements and pressure fluctuations.

Similar attenuation levels with injection of air-fuel mixtures were achieved when the secondary flow was very rich, with equivalence ratios greater than about 3 and injection-Reynolds numbers less than 500 and implied that controllability was related to local enrichment of the flow in the near-wall region under a constraint of minimum imposed strain due to injection. Time-dependent injection with four pneumatic valves at a frequency of up to 15Hz showed no benefits in controlling the low-frequency oscillations. The velocity is inversely proportional to the instantaneous area of the injection orifice for a constant injection flow rate, so that the flame experienced higher imposed strains in the first 15 ms of injection, the time required for the valve to open fully, and then recovered more slowly.

The combination of **added fuel and imposed oscillations** was investigated using the preferred injection arrangement as determined above, and in relation to near-limit and near-stoichiometric oscillations. The objective was to increase stabilisation with the continuous injection of fuel and control the acoustic or bulk-mode frequency with oscillations imposed on the pressure field.

Oscillations were imposed at 290 Hz in the open duct, the five-quarter wave of the entire duct, with equivalence ratios close to the lean flammability and stoichiometric limits, and the quarter and three-quarter wave frequencies were attenuated by 2.6 and 1.7 decades, respectively. These reduced acoustic amplitudes meant that 50% less fuel had to be injected to achieve the same attenuation of the low-frequency oscillations. Thus the r.m.s of pressure was reduced from 0.47 to 0.3 kPa with 1.3% injection at a bulk-flow Reynolds number of 68,000 and equivalence ratio of 0.65. The combination of added fuel and imposed oscillations was even more effective at flow conditions where acoustic frequencies dominated, with a reduction in the r.m.s. of pressure with imposed oscillations and 1.5% injection from 1.7 to 0.8 kPa. at equivalence ratio of 0.90 and Reynolds number of 60,000.

Oscillations imposed at the three-quarter wave frequency of the upstream section of the confined duct with small quantities of injected fuel attenuated the bulk-mode considerably so that the r.m.s of pressure was reduced from 2.5 to 0.5 kPa at equivalence ratios close to stoichiometry and by rather lower percentages close to the lean limit.

CONCLUDING REMARKS

The existence of low-frequency oscillations has been demonstrated in a range of geometrical configurations in which flames were stabilised on ducted plane and round sudden expansions with and without nozzles. The experiments in the round ducts were extended to include the effects of disk stabilisation and swirl. Low-frequency oscillations were present in all cases and at all equivalence ratios, with time scales consistent with periodic extinction caused by high strain rates in the vicinity of the stabiliser and relight by reduction in the strain rate and propagation through the region of recirculating flow.

Close to stoichiometry, the oscillations caused by extinction and relight modulated the dominant acoustic oscillations and precluded the active control of amplitude with imposed oscillations as the rate of heat release was increased. Close to the limits however, they dominated the flow with frequencies and amplitudes increasing with flow rate and the latter by two orders of magnitude when an exit nozzle was added, due to coupling with bulk-mode oscillations. Since the flows were turbulent, the strain rate and length of the region of recirculating flow varied and this led to the range of frequencies of these oscillations and of the resulting modulations.

The phenomena associated with extinction and relight were investigated in laboratory-scale arrangements with reactants at ambient temperatures and pressures, and inlet velocities of the order of 10 m/s. The following considers their implications for practical gas-turbine configurations and operating conditions that can involve preheat temperatures up to 800 K, pressures between 10 and 30 bar, and velocities of the order of 100 m/s. The higher velocities imply larger strain rates and an average time for the movement away from the stabiliser of less than 0.001 s so that it is again likely that the flame movement towards the stabiliser determines the frequency of the oscillations. The burning velocity increases with the square of the temperature and decreases with the square-root of pressure and larger frequencies than those of the laboratory experiments can be expected. With equivalence ratio, combustor temperature and pressure of 0.8, 1500 K and 20 bar, the burning velocity would be around 2.5 m/s and the time required for the flame to travel a recirculation distance of 0.025 m would be around 0.01 s, thus implying an oscillation frequency of around 100 Hz. Thus it is likely that oscillations caused by extinction and relight will exist in engineering practice and the expected increase with heat release suggests amplitudes much larger than those reported here. The resonant frequencies associated with the bulk and longitudinal acoustic modes of larger combustors are often of the order of 100 Hz though radial and circumferential modes may give rise to higher values. Thus, practical combustors may involve a range of natural frequencies and there is a strong possibility of coupling with the oscillations due to extinction and relight. The present results have shown that high amplitudes are associated with coupling and can readily lead to substantial movements of the flame front, flashback and extinction. Flashback is more likely when pre-heated reactants and thicker boundary layers make it easier for the flame to travel upstream of the stabiliser, and this safety hazard often limits the use of premixed combustion in propulsion systems.

Large-amplitudes of oscillation, particularly with flashback, are almost always undesirable and can lead to structural damage. Close to the limits, the increased oscillatory amplitudes have the added drawbacks of narrowing the flammability range by introducing additional strain rates, and of increasing NOx emissions by increasing the residence time at higher temperatures.

The suppression of oscillations in practical combustors is important and generally makes use of an oscillating the fuel supply out-of-phase with the combustion oscillations, as by Poppe *et al.* The present results have shown that imposed pressure oscillations led to reductions of the bulk-mode oscillations of the constricted ducts and, thereby, in the amplitudes of the low-frequency oscillations caused by extinction and relight with which they coupled close to the limits. Thus, it was possible to suppress coupled oscillations through the near-discrete frequency of the acoustic mode but the low-frequency oscillations and the modulations caused by them remained and could not be removed with the actuators used here.

It is clear that the extinction and relight oscillations are related to stabilization and that this can be improved by the injection of richer mixtures of fuel and air. Experiments were performed to quantify this expectation and showed that injection of between 1 and 5% of fuel added at four equally separated circumferential locations, led to improved stabilization and that constant flows of fuel or rich fuel-air mixtures offered advantage over time-dependent ones. The preferred location for adding the fuel proved to be upstream of the plane of the sudden expansion and normal to the surface of the duct. Low-frequency modulations were attenuated and the pressure fluctuations were reduced by about 30% at lean and near-stoichiometric conditions, compared to the naturally-occurring flows. In the confined duct and due to the proximity of the low-frequency and bulk-mode oscillations, the improved flame stabilisation reduced the pressure fluctuations by up to 80%.

The combination of added fuel and imposed oscillations was also investigated and showed that it provided the most effective means of controlling the oscillations at all equivalence ratios in both the open and confined ducts. It was found that approximately 50% less fuel was necessary to achieve the same or better levels of control with imposed oscillations probably because the acoustic and strain-related frequencies were coupled.

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